

Search for anomalous single production of the fourth SM family quark decaying into a light scalar

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Abstract

Superjet events observed by the CDF Collaboration are interpreted as anomalous single production of the fourth SM family u_4 quark, decaying into a new light scalar particle. The specific predictions of the proposed mechanism are discussed.

Recently, CDF Collaboration has reported [1] the observation of an excess of events in $W + 2, 3$ jet topologies, the so called “superjet” events, in which a single jet has both a soft lepton and a secondary vertex. These events are interpreted in [2] as scalar quark \tilde{b} with a mass of 3.6 GeV and a lifetime of 1 ps, decaying into $cl\tilde{\nu}$ where scalar neutrino is assumed to be massless. In our opinion, this interpretation favors the MSSM scenario with superpartner of the right-handed neutrino as the LSP [3], because LEP experiments put the limit $m_{\tilde{\nu}} > 44$ GeV on the mass of superpartners of the left-handed neutrinos [4]. As mentioned in [5], at least some of these events could be explained as anomalous single production of the fourth SM family (see [6] and the references therein) quarks via the process $u_4 \rightarrow tg \rightarrow Wbg$. The superjet is associated with the normal b quark decay. However, this interpretation leads to an essential excess in single tag events, which is several times larger than CDF observations [1].

In this letter, we give another interpretation to superjet events. Following our previous study [5], we still assume that the production is due to anomalous $q_4 qg$ interaction but the decay chain is changed to $u_4 \rightarrow tx^0 \rightarrow Wb\tau^+\tau^-$. The new proposed particle x^0 must have a mass around 4 – 5 GeV. In this mechanism, superjet is formed by the decay of one τ leptonically and the other one hadronically. There are two possible identifications of x^0 . One possibility is the lightest neutral Higgs boson in SM with extended Higgs sector. The other one is a light neutral dilepton which is expected in preonic models.

The effective Lagrangian for the anomalous interactions between the fourth family quarks, ordinary quarks and the gauge bosons V ($V = \gamma, Z, g$) can be written as follows:

$$L = \frac{\kappa_\gamma^{q_i}}{\Lambda} e_q g_e \bar{q}_4 \sigma_{\mu\nu} (A_\gamma^{q_i} + B_\gamma^{q_i} \gamma_5) q_i F^{\mu\nu} + \frac{\kappa_Z^{q_i}}{2\Lambda} g_Z \bar{q}_4 \sigma_{\mu\nu} (A_Z^{q_i} + B_Z^{q_i} \gamma_5) q_i Z^{\mu\nu} + \frac{\kappa_g^{q_i}}{\Lambda} g_s \bar{q}_4 \sigma_{\mu\nu} (A_g^{q_i} + B_g^{q_i} \gamma_5) T^a q_i G_a^{\mu\nu} + h.c. \quad (1)$$

where $F^{\mu\nu}$, $Z^{\mu\nu}$, and $G^{\mu\nu}$ are the field strength tensors of the photon, Z boson and gluons, respectively; T^a are Gell-Mann matrices; e_q is the charge of the quark; g_e , g_Z , and g_s are the electroweak, and the strong coupling constants respectively. $g_Z = g_e / \cos \theta_W \sin \theta_W$ where θ_W is the Weinberg angle. $A_{\gamma,Z,g}^q$ and $B_{\gamma,Z,g}^q$ are the magnitudes of the neutral currents; $\kappa_{\gamma,Z,g}$ define the strength of the anomalous couplings for the neutral currents with a photon, a Z boson and a gluon, respectively; Λ is the cutoff scale for the new physics. We assume all the neutral current magnitudes in Eq. (1) to be equal, satisfying the constraint $|A|^2 + |B|^2 = 1$ and take all anomalous couplings as $\kappa_\gamma^{q_i} = \kappa_Z^{q_i} = \kappa_g^{q_i} = 1$. We have implemented the

new interaction vertices into the CALCHEP [7] package to calculate the cross sections and branching ratios. We use the parton distribution function CTEQ5M [8] and the scale $Q = m_{u_4}$.

x^0 as a light Higgs. We require $u_4 t x^0$ coupling to be sufficiently large in order to provide significant $\text{BR}(u_4 \rightarrow t x^0)$. On the other hand, the interaction of x^0 with the intermediate vector bosons should be suppressed in order to avoid contradiction with the LEP data. So, we will denote this particle as a light Higgs boson h^0 . Naturally, the main decay mode of h^0 should be into kinematically allowed heaviest fermions, namely $\tau^+ \tau^-$ and $c \bar{c}$. In the case of $h^0 \rightarrow \tau^+ \tau^-$, the branching ratios into possible final states are 0.44 for superjet, 0.12 for all lepton mode, 0.43 for all hadron mode. Similar numbers are valid for $h^0 \rightarrow c \bar{c}$. In order to have the lifetime of h^0 to be less than 1 ps, the coupling constant a_τ in the interaction term $a_\tau h^0 \bar{\tau} \tau$ should be larger than 5×10^{-7} .

The number of superjet events can be estimated as

$$N_s = \sigma(gq \rightarrow u_4) \cdot \text{BR}(u_4 \rightarrow t h^0) \cdot \text{BR}(t \rightarrow bW) \cdot \text{BR}(h^0 \rightarrow \text{superjet}) \cdot \text{BR}(W \rightarrow e\nu + \mu\nu) \cdot \epsilon \cdot L_{int} \quad (2)$$

where ϵ stands for detection efficiency. In Table 1, we present production cross section, branching ratios and total decay width for u_4 at different mass values, assuming $\text{BR}(u_4 \rightarrow t h^0) = 10\%$. This assumption corresponds to $b_{tu_4} \approx 0.1$ where b_{tu_4} is the coupling in the interaction term $b_{tu_4} h^0 \bar{t} u_4$. By taking $\epsilon = 0.25$, $\text{BR}(t \rightarrow bW) = 1$ and $\text{BR}(W \rightarrow e\nu + \mu\nu) = 0.21$, we obtain from Eq. (2) number of superjet events $N_s = 6$ for $m_{u_4} = 300$ GeV and the integrated luminosity $L_{int} = 106 \text{ pb}^{-1}$.

x^0 as a light dilepton. Second candidate for the identification of x^0 is a neutral dilepton with zero lepton number [9]. So, we denote this particle as D_τ^0 . The difference between D_τ^0 and h^0 decay modes is that D_τ^0 decays into $\tau^+ \tau^-$ only. D_τ^0 can be produced in u_4 decays via the mixing with a diquark D_q^0 , interacting with u_4 and t (for classification of diquarks see [10]):

$$D_1^0 = D_\tau^0 \cdot \cos \theta + D_q^0 \cdot \sin \theta \quad (3)$$

$$D_2^0 = -D_\tau^0 \cdot \sin \theta + D_q^0 \cdot \cos \theta \quad (4)$$

where θ is the mixing angle. Therefore, u_4 decay chain becomes $u_4 \rightarrow t D_1^0 \rightarrow W b \tau^+ \tau^-$, where we identify x^0 as D_1^0 , and D_2^0 is assumed to be heavy. In order to obtain $\text{BR}(u_4 \rightarrow$

TABLE I: Branching ratios (%), total decay widths for u_4 and production cross section $\sigma(p\bar{p} \rightarrow u_4 X)$ with $\Lambda = 2$ TeV.

| Mass (GeV) | $gu(c)$ | gt | $Zu(c)$ | Zt | $\gamma u(c)$ | γt | Γ (GeV) | σ (pb) |
|------------|---------|------|---------|------|---------------|------------|----------------|---------------|
| 200 | 42 | 0.54 | 2.0 | - | 0.90 | 0.028 | 0.39 | 33.4 |
| 250 | 40 | 5.2 | 2.2 | - | 0.83 | 0.11 | 0.81 | 25.9 |
| 300 | 37 | 11 | 2.2 | 0.41 | 0.77 | 0.23 | 1.50 | 24.8 |
| 400 | 32 | 17 | 2.1 | 1.0 | 0.69 | 0.37 | 3.96 | 21.8 |
| 500 | 31 | 21 | 2.0 | 1.4 | 0.66 | 0.44 | 8.20 | 15.2 |
| 600 | 30 | 23 | 2.0 | 1.5 | 0.64 | 0.49 | 14.67 | 9.4 |
| 700 | 30 | 24 | 2.0 | 1.6 | 0.62 | 0.51 | 23.80 | 5.1 |

$t D_1^0$) = 10%, one needs $b \sin \theta = 0.1$ where b is the coupling constant of the $D_q^0 u_4 t$ interaction.

To test the proposed mechanism, we have reconstructed the invariant mass of the $W + j$ system where j denotes the ordinary jet accompanying the superjet, using the $W + 2$ jet events in Table XVI of [1]. The resulting mass values are 159, 175, 600, 159, 178, 228, 172, 149 GeV. The third and the sixth events do not reproduce the expected top quark mass value and probably they are due to SM background.

Another prediction of our mechanism is the occurrence of spectacular events with collinear $e\mu$ tracks originating from x^0 when both τ leptons decay leptonically. Ratio of the number of events of this type to the number of superjet events should be 1 : 15 for h^0 and 1 : 8 for D_τ^0 . Therefore, we expect the observation of a number of collinear $e\mu$ tracks at the upgraded Tevatron with integral luminosity 1 fb^{-1} .

In conclusion, CDF superjet events seem to indicate very exciting physics at TeV scale. Namely, existence of the fourth SM family, anomalous interactions, extended SM Higgs sector etc. The scale $\Lambda = 2$ TeV can be a hint of relatively low scale compositeness which will lead to a rich *zoo* of new particles at the LHC.

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